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Treatment of Tumors with Genetically Engineered Herpes Virus

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Abstract

Disclosed are methods for treating cancer by administering an effective amount of a modified Herpes simplex virus.

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ORIGINAL

COMPLETE SPECIFICATION

STANDARD PATENT

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Invention Title: "Treatment of Tumor with Genetically Engineered Herpes Virus"

The following statement is a full description of this invention, including the best method of performing it known to me:-

TREATMENT OF TUMORS WITH GENETICALLY ENGINEERED HERPES VIRUS

FIELD OF THE INVENTION

The present invention relates generally to use of modified Herpes simplex viruses as therapeutic treatment for tumors.

BACKGROUND OF THE INVENTION

The development of viruses as anticancer agents has been an intriguing yet elusive strategy. The goal of anticancer viral therapy is to inoculate a small percentage of tumor cells with replication competent viruses resulting in viral replication in the targeted tumor cells followed by cellular lysis (oncolysis) and infection of surrounding tumor cells. A key to viral oncolysis is genetic modification of the virus such that replication occurs principally in tumor cells and not in the surrounding normal tissue. Many strategies have focused on the use of genetically engineered viruses for oncolysis. For example, in one approach, attenuated retroviruses, modified to encode herpes simplex virus (HSV) thymidine kinase, were created to target dividing tumor cells [Culver, *et al.*, *Science 256*:1550-1552 (1992); Ram, *et al. Nat. Med. 3*:1354-1361 (1997)]. In this technique, however, viral infection of tumor cells was limited since only 10 to 15% of tumor cells were actively progressing through the cell cycle. In another approach, conditional replication-competent adenoviruses (E1b deleted) were designed to replicate only in tumor cells lacking p53, however only 50% of tumors are estimated to contain nonfunctional p53 [Bischoff, *et al.*, *Science 274*: 373-376 (1996); Heise, *et al. Nat. Med. 3*:639-645 (1997); Hollstein, *et al.*, *Science 253:* 49-53 (1991)]. The success of these strategies, therefore has been limited experimentally only to small tumor xenografts.

Recently, genetically engineered replication-competent HSV has been proposed to treat malignant gliomas [Martuza, *et al.*, *Science 252:*854-856 (1991)]. In anti-glioma therapy, HSV-1 mutants were constructed to preferentially replicate in proliferating tumor cells thereby eliminating the risk of widespread dissemination of the virus in the central nervous system, which is observed in rare cases of HSV encephalitis in human. Initial strategies focused on deletion of viral genes encoding enzymes required for viral DNA synthesis (*e.g.*, thymidine kinase, ribonucleotide reductase [Martuza, *et al.*,

Science 252:854-856 (1991); Mineta, *et al., Cancer Res. 54*: 3963-3966 (1994)]. More recent studies centered on the use of HSV mutants that lack a newly identified $\gamma_1 34.5$ gene involved in neurovirulence [Chou, *et al., Science 250*:1262-1266 (1990); Chou, *et al., Proc. Natl. Acad. Sci. (USA) 89*:3266-3270 (1992); Chou, *et al., Proc. Natl. Acad. Sci. (USA) 92*:10516-10520 (1995); Andreansky, *et al. Cancer Res. 57*:1502-1509 (1997)]. The combination of previous results suggested that a decrease in viral proliferative potential required for safe intracranial HSV inoculation, however, correlates with a decrease in the oncolytic potential of the virus [Advani, *et al. Gene Ther. 5*:160-165 (1998)]. The potential therapeutic effects of a genetically engineered HSV, having more potent antitumor efficacy than is possible for intracranial inoculation, has not been studied in models of common human tumors.

HSV offers many advantages as an oncolytic agent. The virus replicates well in a large variety on cancer cells and it destroys the cells in which it replicates. The virus can be attenuated by introducing specific deletions and it tolerates the insertion and expression of foreign genes [Meignier, *et al., J. Infect. Dis. 158*:602-614 (1988)]. Moreover, the functions of many HSV viral genes are known [Shih, *et al., Proc. Natl. Acad. Sci. (USA) 81*:5867-5870 (1984); Roizman, *Proc. Natl. Acad. Sci. (USA) 93*:113076-11312 (1996)]. The undesirable properties of HSV, however, include neuroinvasiveness, the ability to establish latency, and a capacity for reactivation from latent state.

Previous work has shown interactive effects of cytolytic capacity of modified HSV lacking both $\gamma_1 34.5$ genes and ionizing radiation on glioma xenografts [Advani, *et al. Gene Ther. 5*:160-165 (1998)]. Ionizing radiation combined with inoculation with $\gamma_1 34.5$-deficient HSV viruses resulted in supra-additive reduction in tumor xenograft volume and an enhancement in viral proliferation and intra-tumoral distribution in glioma xenografts.

R7020 is one such HSV strain attenuated by genetic engineering and tested in a variety of rodent, rabbit, and non-human primate models [Meignier, *et al., J. Infect. Dis. 158*: 602-614 (1988); Meignier, *et al., J. Infect. Dis. 162*:313-321 (1990)] which have shown that viral infectivity is attenuated in all species tested. A key property of interest in this strain is the lack of neuroinvasiveness even in the most susceptible species

tested to date. R7020 is a modified HSV strain designed as a candidate for human immunization against HSV-1 and HSV-2 infections [Meignier, *et al., Infect. Dis. 158*: 602-614 (1988)]. Originally produced to be a live attenuated viral vaccine against HSV infection, R7020's has been examined for safety and stability in rodent and primate studies [Meignier, *et al., J. Infect. Dis. 158*: 602-614 (1988); Meignier, *et al., J. Infect. Dis. 162*:313-321 (1990)]. The construction of R7020 has been previously described [Meignier, *et al., J. Infect. Dis. 158*: 602-614 (1988); and Roizman, U.S. Patent No: 4,859,587, incorporated herein by reference]. Briefly, wild-type HSV DNA consists of two regions of unique double-stranded DNA sequences flanked by inverted repeats [Roizman, *et al., Proc Natl. Acad. Sci. (USA) 93*:11307-11312 (1996)]. The inverted repeats regions contain two copies of five genes designated $\alpha0$, $\alpha4$, $\gamma_1 34.5$, ORF P and ORF O. R7020 contains an HSV-2 DNA fragment inserted in place of one set of the repeats and therefore lacks only one of the two copies of the $\gamma_1 34.5$ gene. Previously work has shown that, in certain cell lines, R7020 replicates more efficiently than viruses lacking both copies of the $\gamma_1 34.5$ gene [Advani, *et al. Gene Ther. 5*:160-165 (1998)]. To date, R7020 has been subjected to limited trials in humans.

One of the causes of failure in cancer therapy is tumor cell resistance to conventional cytotoxic and/or hormonal treatments that arises from genetic instability caused by these agents and inherent instability of tumor cells. For example, p53 gene deletion or mutation may decrease tumor cell susceptibility to apoptosis induced by chemotherapy and/or radiation [Houldsworth, *et al., Oncogene 16*:2345-2349 (1998); Aas. *et al. Nat. Med. 2*: 811-814 (1998); Lowe, *et al., Science 266*:807-810 (1994); Dalta, *et al., Cell Growth Differ. 6*:363-370 (1995)] and mutations in the androgen receptor lead to hormone resistance in prostate cancer. Also, "gain of function" mutations, such as activation of the bcl-2 family of genes, enhances resistance to a variety of cytotoxic therapies. In addition to intrinsic genetic instability of tumor cells, commonly employed anticancer therapies that rely on DNA damage to tumor cells are mutagenic and a consequence of anticancer treatment is the selection and evolution of resistance to DNA damaging agents. One benefit of using viral lysis as an antitumor strategy is that viral lysis has the potential to overcome tumor resistance to conventional agents. Since tumor cell infection with replication component herpes results in cell lysis and is not *per se*

mutagenic, selective evolution of tumor cells to evade herpes is less likely to occur within the tumor cell population.

Thus there exists a need in the art to identify and develop viral therapeutic agents and effective methods of treatment to retard and/or reduce tumor growth in patients in need thereof.

SUMMARY OF THE INVENTION

The present invention provides methods for treating cancer comprising the steps of administering to an individual in need thereof an effective amount of a Herpes simplex virus (HSV) comprising a modified HSV genome wherein said modification comprises a modification of an inverted repeat region of said HSV genome. In one embodiment, methods of the invention include use of HSV strains wherein the modification of the inverted repeat region of the genome comprises an alteration of a copy of a $\gamma 134.5$ gene that renders that copy of the gene incapable of expressing an active gene product. In a preferred embodiment, methods of the invention comprise use of an HSV strain wherein the alteration of the $\gamma_1 34.5$ gene comprises (i) an insertion of a DNA sequence comprising one or more nucleotides into the coding region or regulatory region of the gene or (ii) a deletion of all or part of the coding region or regulatory region of the gene. Methods of the invention include use of HSV strains wherein the modified HSV genome further comprises an alteration in a unique region of the HSV genome.

Methods of the invention include treatment of noncentral nervous system cancer as well as central nervous system cancer.

DETAILED DESCRIPTION

The present invention provides materials and methods for treating a variety of tumors including noncentral nervous system tumors and tumors of the central nervous system origin. The treatment methods involve infecting target tumors with genetically modified herpes simplex virus wherein the modification comprises a modification of an internal inverted repeat region of the herpes simplex virus genome. In a preferred embodiment the modification of the herpes simplex virus genome comprises the deletion of one copy of the internal repeat sequence of the viral gene which region comprises one

copy each of ICP0, IPC4, ORFO, ORFP and $\gamma_1$34.5 genes. The herpes simplex viruses useful in the practice of the invention are attenuated with respect to the wild-type herpes simplex viruses but are more replication competent than viruses having both copies of the inverted repeat region modified (to render the region incapable of expressing an actual gene product of any one of the various genes) or deleted. Viruses useful in the practice of the present invention may have additional alterations in their genome that may include insertion of expressible non-natural protein encoding sequences under the control of herpes simplex virus promoters that in turn permits the sequence to be regulated as an α, β or γ class of herpes simplex virus genes that are well known in the art. [See, *e.g.* *Fundamental Virology, Second Edition*, Field *et al.*(eds.) Chapters 33-34, Raven Press Ltd., New York (1991) incorporated herein by reference.] Viruses lacking internal repeated can be further attenuated if necessary by the deletion of one or more of the 47 genes found dispensable for viral replication in culture [Roizman, *Proc. Natl. Acad. Sci. (USA)* (1996)]. Among the genes suitable for deletion to decrease further virulence are the U_L16, U_L40, U_L41, U_L55, U_L56, α22, U_S4, U_S8, and U_S11 genes. Deletion of virtually any one of the "dispensable" genes will reduce virulence by a factor ranging from twofold to several logs. In addition, candidate viruses lacking the internal inverted repeats may be further altered by the addition of cytokines, as well as enzymes that activate prodrugs.

Herpes viruses useful in the practice of the invention may be prepared using methods well known in the art such as methods described in U.S. Patent No. 4,859,587 (incorporated herein by reference.) and in U.S. Patent No. 5,288,641 (also incorporated herein by reference.)

The examples set out below describe the use of herpes simplex virus type HSV-1 strain R7020 to reduce tumor size in mice. The use of mice as models for the treatment of tumorogenic disease is well known and widely accepted in the art. Example 1 describes the structure of HSV-1 strain R7020 which virus strain is illustrative of the kinds of genetically modified viruses that are useful in the practice of the present invention. Example 2 describes the use of a modified HSV-1 to reduce the tumor volume of a grafted epidermal carcinoma cell line in mice.

Example 3 describes the kinetics of viral replication in the epidermal carcinoma xenografts described in Example 1. The experiments described in Example 4

establish that epidermal carcinoma arising from residual tumor cells retain their susceptibility to infection by HSV-1 R7020.

The following examples are presented by way of illustration and are not intended to limit the scope of the invention as described in the appended claim.

Example 1
Structure of HSV Strain R7020

The structure of R7020 (A.T.C.C. Accession No: VR2123, deposited December 10, 1985), as described previously [Meignier, *et al.*, *J. Infect. Dis. 158*:602-614 (1988)] includes an insertion comprising a *Hin*dIII fragment of HSV-2 DNA encompassing gene sequences encoding several glycoproteins inserted into the joint region of the parental HSV genome. A detailed analysis of the R7020 structure revealed differences from those reported by Meignier, *et al.* as described below.

First, insertion of the HSV-2 sequence leaves intact the parental HSV-1 U_L55 gene whereas previous reports showed that part of the U_L55 gene was deleted. The U_L55 gene, however has no known function and probably does not affect safety of the virus. In addition, the U_L55 region is preceded by 300 bp of "unknown sequence" at the joint region. As previously reported, the U_L56 region that has been implicated in pathogenesis [Kehm, *et al.*, *Virus Res 40*:17-40 (1996)] was not found in the corrected sequence.

Second, the U_L56 sequences are duplicated at the joint region, which probably leads to defective genomes arising in a predictable and reproducible manner. Defective genomes are known to arise spontaneously in HSV-1 stocks if passaged at high multiplicity and defective genomes arise in R7020 more reproducibly and frequently. However, passage at low multiplicity of infection as is routine, minimizes the accumulation of defective genomes.

In another difference, only 5229 bp of the originally predicted 9629 bp of HSV-2 sequence were found in R7020.

Example 2
Volumetric Reduction of Tumor Xenograft

In a first series of experiments, SQ-206 cells, a chemotherapy/radiation-

resistant epidermal carcinoma cell line that expresses a nonfunctional p53, or PC-3 cells, a hormone-independent $p53^{+}$ prostate adenocarcinoma cell line, were injected into the hindlimb of nude mice. SQ-20b is an epidermal cancer cell line isolated from a patent following radiotherapy as described elsewhere [Hallahan, *et al. Nat. Med. 1*:786-791 (1995)]. PC-3 cell line was obtained from American Type Culture Collection (A.T.T.C. No. CRL 1435, Manassas, VA). Large tumor xenografts were employed to approximate the relative mass of clinically evident, locally advanced human cancers. In contrast to earlier studies carried out with a tumor mass of approximately 100 mm^3, the experiments in this series were performed with tumors having a mean initial volume of 630 mm^3 corresponding roughly to 3% of mouse weight [Ram, *et al. Nat. Med. 3*:1354-1361 (1997)]..

Briefly, SQ-20b tumor cells in amounts of 5×10^5 cells per mouse were suspended in 100 µl of sterile phosphate buffered saline (PBS), injected into the right hind limb of 5 to 6 week old athymic nu/nu mice, and grown to a tumor size of 200 to 1000 mm^3. The mouse hindlimb model has been described elsewhere in detail [Advani, S.J. et al. Gene Ther. 5, 160-165 (1998)]. As previously reported, its major advantage is that it allows the measurement of the effects on oncolytic agents without recourse to invasive procedures. The previously described model was modified to increase the mean size of the xenograft from 100 to 600 mm^3 at the time treatment by virus injection was initiated, to increase the ratio of cells to virus and approximate more closely the size of the tumor in clinically relevant situations.

Mice were randomized into two treatment groups: (a) controls administered 10 µl of a buffer solution and (b) mice administered 2×10^6 plaque forming units (pfu) of R7020 in 10 µl of buffer with a Hamilton syringe. The genetically engineered R7020 virus is derived from HSV-1(F) which is the prototype HSV-1 virus [Meignier, *et al., supra*]. R7020 lacks U_L24, U_L56, and one set of the inverted repeats encoding one copy of the genes $\alpha0$, $\alpha4$, $\gamma_1 34.5$, ORFP and ORFO. The deleted region of the internal inverted repeat of HSV-1(F) was replaced by a DNA fragment encoding HSV-2 glycoproteins G, J, D, and I [Meignier, *et al., J. Infect. Dis. 158*:602-614 (1988)]. Virus was titered on Vero cells (American Type Culture Collection, Manassas, VA) as described elsewhere [Chou, *et al., Science 250*:1262-1266 (1990)]. The tumor mass was

measured biweekly or until tumor volume reached 2000 mm^3. Tumor volumes were calculated using the formula (length x width x height)/2 which is derived from the formula of an elipsoid (δd^3)/6. Animal studies were performed according to a protocol approved by the Animal Resource Center at the University of Chicago. Fraction tumor volume was defined as tumor volume at the specific time point divided by the initial volume (V/V_0). Animals were sacrificed when tumor volume exceeded 2000 mm^3. Similar experiments were carried out with PC-3, with the only exception that 2 x 10^7 cells in 100 µl of PBS were injected per xenograft.

Result indicated that SQ-20b xenografts treated with R7020 began to regress 13 days after infection and reached a nadir at 41 days post-infection at which time the mean tumor volume reduction was down to one fifth of the initial tumor volume. Seventy two percent (8 of 11) of the tumor xenografts regressed to less than 10% of the initial tumor volume by day 41, and 7 of these 8 retained the reduced size for greater than 80 days.

R7020 was effective in tumor volume regression of PC-3 prostate adenocarcinoma xenografts as well. Fractional tumor volume achieved a nadir approximately 20 to 30 days after infection. R7020 was also as effective in causing regression of a hepatoma adenocarcinoma tumor xenograft.

Example 3
Kinetics of Viral Replication in SQ-208 Xenografts

In order to assess the kinetics of viral replication in the SQ-208 xenografts, the following procedures were carried out. SQ20 xenografts were injected with 2 x 10^6 pfu of R7020 or with buffered saline. The mice injected with virus were divided into two groups. One group was sacrificed at specified times. Tumors were aseptically harvested at specific time points after infection, snap frozen in liquid nitrogen, and stored at -70°C. Tumors were homogenized in 1 ml of 199V and 1 ml of sterile skim milk for 20 seconds on ice using a Polytron tissue homogenizer (Kinematics, Switzerland). The homogenate was sonicated three times for 15 seconds each and virus was titered on Vero cells.

The tumor volumes in mice injected with saline and those of the second group of identically treated mice injected with virus were tested for tumor volume. As in the experiment described in Example 2, tumors injected with buffered saline grew

exponentially whereas tumors injected with virus regressed. Viral titers peaked at seven days after infection with 124 x 10^5 pfu/tumor, *i.e.*, a 62-fold increase in virus over the amount injected into the tumors. Significant amounts of virus (greater than 10^5 pfu) were recovered at late as 30 days after infection.

Example 4
Tumor cells Resistance to Oncolytic Effects of R7020

In order to assess the ability of SQ-20b tumor cells to become resistant to the oncolytic effects of R7020, the following experiments were performed.

Tumors were grown as described above. When tumors were greater than 200 mm^3, they were injected with 2 x 10^6 pfu of R7020 in 10 μl of buffer on day 0. Tumors were measured biweekly. As tumors regrew to their starting tumor volume (volume at day 0), they were randomized and re-injected with either 10 μl of buffer, 2 x 10^6 pfu of R7020, or 2 x 10^6 pfu of HSV-1(F) in the same volume of buffer. Animals with tumor volume greater than 200 mm^3 were sacrificed following institutional guidelines.

Results indicated that all three buffer re-injected tumors continued to increase the size. Fractional tumor volume decreased following the second viral injection of either R7020 or HSV-1(F). Tumors continued to show sensitivity for viral oncolysis through two cycles of R7020 injection and did not recur for at least 120 days from the initiation of the experiment. Mice reinjected with HSV-1(F) died four to six weeks following wild-type virus injection whereas mice reinjected with R7020 thrived. Thus, SQ-20b tumors arising from residual cells in tumors previously treated with R7020 retain susceptibility to infection.

Example 5
R7020 Treatment in Combination with Irradiation

Earlier studies on glioma xenografts have shown that the combination of irradiation and administration of an attenuated HSV result in enhanced tumor cell destruction as well as enhanced viral replication [Advani, *et al. Gene Ther.* *5*:160-165 (1998)]. To determine whether irradiation of the radiation-resistant SQ-206 cell lines enhanced the oncolytic effect of R7020, xenografts were infected as described above and subjected to a fractionated irradiation protocol as described below.

Irradiation of xenografts was carried out as described elsewhere [Advani, *et al. Gene Ther.* 5:160-165 (1998)]. Briefly, tumor-bearing hindlimbs were exposed to ionizing radiation using a GE 250 kv maxitron generator (191 cGy/min, 150 kVp). Irradiation was administered starting six hours after infection with R7020 in 400 cGy fractions on Monday, Tuesday, Thursday, and Friday for two weeks up to a maximum dosage of 3200 cGy. Fractionated irradiation was administered in doses routinely employed in clinically relevant protocols.

Results indicate that irradiation alone resulted in a modest delay in xenograft growth compared to control tumors confirming radiation resistance of the SQ-206 cell line. While tumor volume reduction did not occur until 13 days after infection of xenografts with R7020 as described in Example 2, combining irradiation with R7020 resulted in tumor volume regression one week earlier than tumors treated with R7020 alone. In addition, the nadir in tumor volume occurred significantly earlier in xenografts receiving both irradiation and R7020 as compared to xenografts receiving R7020 alone (day 20 versus day 30).

These results demonstrate for the first time dramatic antitumor efficacy of R7020 in the treatment of experimental human tumors frequently resistant to common cancer treatments and suggest that, while R7020 is an effective antitumor agent by itself, combining irradiation with R7020 also provides more rapid and complete tumor cell destruction. The combination of irradiation and attenuated HSV as an anticancer therapy may prove to be especially beneficial in clinical situations where the tumor burden may be too large for single agent therapy.

Numerous modifications and variations in the invention as set forth in the above illustrative examples are expected to occur to those skilled in the art. Consequently only such limitations as appear in the appended claims should be placed on the invention. References cited herein are incorporated by reference in their entireties.

Throughout the specification, unless the context requires otherwise, the word “comprise” or variations such as “comprises” or “comprising”, will be understood to imply the inclusion of a stated integer or group of integers but not the exclusion of any other integer or group of integers.

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The Claims Defining the Invention are as Follows

1. Use of a genetically modified Herpes simplex virus (HSV) comprising a modification of an inverted repeat region of the HSV genome such that the region is rendered incapable of expressing an active gene product from only one copy each of the ICP0, ICP4, ORFO, ORFP and $\gamma_1$34.5 genes for the manufacture of a medicament for treating cancer.

2. Use according to claim 1, wherein the modification is a deletion of only one copy of the inverted repeat sequence comprising one copy each of the ICP0, ICP4, ORFO, ORFP, and $\gamma_1$34.5 genes.

3. Use according to claim 1 or 2, wherein the HSV is further attenuated by deletion of one or more genes selected from α0, UL2, UL3, UL4, UL10, UL11, UL12, UL12.5, UL13, UL16, UL20, UL21, UL23, UL24, UL39, UL40, UL41, UL43, UL43.5, UL44, UL45, UL46, UL47, UL50, UL51, UL53, UL55, UL56, α22, US1.5, US2, US3, US4, US5, US7, US8, US8.5, US9, US10, US11, α47, Ori_STU, and LATU.

4. Use according to claim 3, wherein the genes are selected from UL16, UL24, UL40, UL41, UL55, UL56, α22, US4, US8 and US11.

5. Use according to claim 4, wherein the HSV comprises deletions of UL24 and UL56.

6. Use according to any one of claims 2 to 5, wherein the deletion is carried out by an insertion.

7. Use according to claim 6, wherein the insertion is a DNA fragment encoding HSV-2 glycoproteins G, J, D and I.

8. Use according to any one of claims 1 to 7, wherein the modified HSV is R7020

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9. Use according to any one of claims 1 to 8, wherein the HSV genome comprises an insertion of expressible non-natural protein encoding sequences under the control of herpes simplex virus promoters.

10. Use according to any one of claims 1 to 9, wherein the cancer is a noncentral nervous system cancer

11. Use according to any one of claims 1 to 9, wherein the cancer is a central nervous system cancer.

12. Use according to claim 1 substantially as herein described with reference to any one of the examples.